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LONG-PERIOD SEISMOLOGICAL RESEARCH PROGRAM

Lynn R. Sykes, et al

Lamont-Doherty Geological Observatory

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PALISADES, NEW YORK 10964

Long-Period Seismological Research Program

Semi-Annual Report

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13. ABSTRACT

During the past six months studies utilizing the VLP data have been initiated that bear directly on the problem of discrimination between earthquakes and explosions in central Asia. The most promising technique involves a comparison of observed Rayleigh-to-Love (LR/LQ) wave ratios from events in a certain region with expected values of LR/LQ based on the tectonic framework of the region. This surface wave technique, which considers both Rayleigh and Love waves may also prove effective in discriminating events that plot in or near an explosion population on an M_S (Rayleigh)-m_b basis. The special cooperative study to determine the surface wave detection thresholds of the VLP stations, using the ISM listing as a data base, is nearing completion. To date, based on a preliminary ISM list, the 90% threshold values of the VLP stations for surface waves from shallow focus ($h<50$km) earthquakes have been found to range from $m_b=4.1$ at epicentral distances (Δ) of 30° to $m_b=4.7$ at $\Delta=90°$. Our investigations of the source (or sources) and behavior of long-period earth noise at the VLP stations have shown that earth noise levels between about 30 and 50 seconds are nearly the same at all the widely varying geographical locations. In addition, the VLP system noise levels between 30 and 50 seconds are at least 15dB below the levels of earth noise. Thus the recognition of the source (or sources) of this earth noise, its effective wave-length, and temporal and geographical behavior could possibly indicate techniques that might result in further improvements in the detection capabilities of the VLP stations.

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TABLE OF CONTENTS

SUMMARY

During the past six months studies utilizing the VLP data have been initiated that bear directly on the problem of discrimination between earthquakes and explosions in central Asia. The most promising technique involves a comparison of observed Rayleigh-to-Love (LR/LQ) wave ratios from events in a certain region with expected values of LR/LQ based on the tectonic framework of the region. This technique has been applied by Tatham and Savino (1973) to surface waves recorded at the VLP station at Albuquerque, New Mexico (ALQ), from swarm-type earthquakes of $m_b = 3.0$ to 5.4 that occurred in the northern Gulf of California. The surface-wave observations indicated that the focal mechanisms of many of the swarm earthquakes were strike-slip, thus, placing them on a fracture zone rather than a ridge center. This result was further corroborated by S-P times from a close-in short period seismograph station which also placed the events on a mapped fracture zone. This surface wave technique, which considers both Rayleigh and Love waves may also prove effective in discriminating events that plot in or near an explosion population on an M_s(Rayleigh)-m_b basis.

The special cooperative study to determine the surface wave detection thresholds of the VLP stations, using the International Seismic Month (ISM) listing as a data base, is nearing completion. To date, based on a preliminary ISM list, the 90% threshold values of the VLP stations for surface waves from shallow focus ($h \leq 50$km) earthquakes have been found to range from $m_b = 4.1$ at epicentral distances (Δ) of 30^o to $m_b = 4.7$ at $\Delta = 90^o$. Statistics on particular problems that affect the detection capabilities of the VLP stations, such as,

masking of small events in the coda of large earthquakes, and degradation of signal-to-noise ratios by microseism storms are being gathered.

Our investigations of the source (or sources) and behavior of long-period earth noise at the VLP stations, particularly the experiment at OGD, have shown that earth noise levels between about 30 and 50 seconds are nearly the same at all of these widely varying geographical locations. In addition, the VLP system noise levels between 30 and 50 seconds are at least 15dB below the levels of earth noise. Thus the recognition of the source (or sources) of this earth noise, its effective wave-length, and temporal and geographical behavior could possibly indicate techniques that might result in further improvements in the detection capabilities of the VLP stations. The experiment at OGD indicates that horizontal-component seismometers should be placed at depths of 150 to 200m below the surface at a hard rock site to minimize the effects of moderate winds and atmospheric turbulence on S/N. Based on this same experiment, however, we conclude that vertical-component seismometers can be operated with very high recording magnifications at substantially shallower depths of burial at hard rock sites.

I. STATION MAINTENANCE

During the past six months of the subject contract the VLP station at Ogdensburg, New Jersey (OGD), was maintained in constant operation. Both the analog (seismograms) and digital data were complete (no gaps) for this period of time. A special air conditioned room was constructed on the 1850' level of the mine observatory. This room is 12' long, 5' deep, and 8' high and houses the digital magnetic tape recorder. Controlling the environmental temperature, humidity, and dust content in this manner should ensure continued dependable operation of the digital tape recorder. Seismograms and magnetic tapes from OGD through September 1973

have been forwarded to Asheville, North Carolina, for microfilming, and AFTAC at Alexandria, Virginia, respectively.

II. RESULTS OF THE DATA ANALYSIS

A. Focal Mechanisms of Small Magnitude Events:

Tatham and Savino (1973) have developed and tested a surface wave technique for studying the focal mechanisms of small magnitude events at teleseismic distances. This technique is now being applied to events in central Asia and may prove to be important to the discrimination between earthquakes and underground explosions in that region. In particular, by considering both Rayleigh and Love waves, we may be able to properly classify as earthquakes occasional small events that occur in certain regions of central Asia and that plot in or near the explosion population on an M_s(Rayleigh)-m_b basis.

The method developed by Tatham and Savino (1973) consists of comparing observed amplitudes of long-period Rayleigh and Love waves with radiation patterns of focal mechanisms consistent with the previously determined tectonic regime of a certain region. It is important to note that in using this method we do not determine focal mechanisms, per se, but rather discriminate between different types of mechanisms thought to be prevalent in a region.

In the study by Tatham and Savino (1973) the relative amplitudes of Rayleigh and Love waves with periods between 10 and 50 seconds were determined for some 60 swarm-type events, assumed to be shallow ($h < 15$km), that occurred near the Delfin basin in the northern Gulf of California. These surface waves were recorded at the new VLP station at Albuquerque, New Mexico (ALQ). The bathymetry and seismicity of the northern Gulf of California suggest that faulting is occurring at short spreading centers (dip-slip faulting) and along transform faults (strike-slip faulting).

The radiation patterns for Love and Rayleigh waves corresponding to the above faulting patterns for the northern Gulf of California are schematically illustrated in Figure 1. All of these patterns were computed assuming double-couple sources and shallow focal depths. The position of the nodes in the radiation patterns for strike-slip faulting are independent of focal depth, but there are changes in the absolute amplitude of the lobes, especially for Rayleigh waves, with variations in focal depth. The dip-slip radiation patterns are for a pure dip-slip mechanism with the fault plane 15° from vertical and zero focal depth. It is important to note that these dip-slip patterns change significantly with increasing focal depth, even to a depth as shallow as 33 km. That is, as depth increases for dip-slip mechanisms, the number of nodes and the number and amplitude of lobes, changes. However, the amplitudes of the surface waves, especially Rayleigh waves, tend to decrease as depth increases, an effect that is especially pronounced for these dip-slip mechanisms. Further, the amplitudes of surface waves generated by near-vertical dip-slip faulting tend to be small at all focal depths. The reader is referred to the paper by Tatham and Savino (1973) for more detailed arguments concerning the focal depths of the swarm events included in this study.

The near optimum azimuthal position of the VLP seismograph station ALQ, with respect to the radiation patterns shown in Figure 1, provides for the possibility of discriminating between the two possible focal mechanisms assumed for the northern Gulf of California. For normal faulting on a spreading center, surface waves radiated on the azimuth

of ALQ should be weak and of approximately equal amplitude distribution in both Love and Rayleigh waves. For strike-slip mechanisms, Love waves should be of much greater amplitude than Rayleigh waves. Figure 2 (a-b) shows examples of the relative excitation of Rayleigh and Love waves by two swarm events recorded on the 3-component VLP seismographs at ALQ. Figures 2a and 2c show the three orthogonal components of each record segment normalized to a common magnification for each event. It is especially evident that the horizontal Love-wave motion dominates over the vertical motion. Further, the observed vertical motion does not have the character of fundamental Rayleigh waves, and may possibly be due to higher modes. Figures 2b and 2d illustrate the result of a rotation of the horizontal components into equivalent radial and transverse traces. Here the Love-wave motion of the transverse component is clearly much greater than the Rayleigh-type motion that would be observed on the vertical and radial components. In addition, the radial motion shows the same lack of fundamental Rayleigh-wave character as that observed for the vertical motion. These few examples demonstrate that Love waves are indeed the dominant surface waves observed at ALQ and from this it was concluded that strike-slip was probably the dominant faulting mechanism.

In total, surface waves from 60 events identified as being part of this swarm were observed at ALQ. In several cases, Love waves an order of magnitude smaller than those in Figure 2a and b, an $m_b = 4.2$ event, were recorded demonstrating the value of the horizontal components and how they

enhance the detection capabilities of a station. This technique should prove extremely useful for events in central Asia in view of the stations KON, TLO, EIL, CHG, and MAT which cover a wide range of azimuths.

B. Detection Capabilities of the VLP Stations

Recently the Seismic Discrimination Group at Lincoln Laboratory compiled a special listing of the occurrence of as many events as possible for the time period 20 February 1972 through 19 March 1972. Hereafter this special listing and the above 1 month time period will be referred to as the International Seismic Month (ISM). To data a preliminary sublisting of the ISM, the verified events, contains 840 entries identified on the basis of short-period body waves recorded on the various arrays (LASA, NORSAR, ALPA); the Canadian, Swedish, and United Kingdom seismograph networks; and the WWNSS stations. The ISM listing serves as an excellent data base to be used in the determination of approximate detection thresholds of the VLP stations. This study will be completed when the final version of the ISM listing is received at Lamont.

As of the present time the determination of detection thresholds has been based primarily on a detailed analysis of the analog recordings (seismograms) from nine of the VLP stations for the number of earthquakes recorded at one or more of these sites. The results of this visual analysis are shown in Figure 3 (a-c).

The histogram in Figure 3a gives an idea of how the VLP stations, either as single stations (e.g., CTA column) or taken together (sum all nine VLP column) fared detection wise in terms of the ISM listing (column headed ISM).

The numbers inside the lightly stippled sections of each of the VLP columns refer to the number of world-wide earthquakes reported in the ISM that excited surface waves of either the Rayleigh or Love type with periods between about 15 to 60 seconds and which were observed at that particular (see column heading) VLP station. Note that about 55% (465) of the 840 reported events were detected at at least one of the VLP stations, more than twice as many than the number detected at any one site. While it is not entirely evident from this figure, the combination of the five stations EIL, FBK, CTA, ALQ, and KON are responsible for more than 90% of the 465 observed events.

The varying heights of the individual VLP columns in Figure 3a reflect the amount of time no records were available from the different stations. For all the stations except KIP and CHG, these times were mainly due to analog record changing intervals; digital data are available for these times. The KIP station became operational on 7 March 1972, more than half way through the ISM time period. This accounts for the relatively small number (281) of events considered. Approximately 7 days of recordings from CHG were late in arriving at Lamont and had not been included in the analysis as of the time Figure 3a was prepared.

Two other important observations that are not obvious from Figure 3a come from the analysis involved in the preparation of this figure. They are the following:

1. Approximately 10% of the events observed at the deep stations EIL, OGD, and KON were observed on the basis of long-period Love waves only. The reason for restricting this statement to the deep stations is that the horizontal component seismographs at these sites operate with peak magnifications equivalent to those of the vertical component systems. In addition

the low noise levels on the horizontal component seismograms from these three stations do not undergo any obvious diurnal variations as do the horizontal noise levels at the other shallower sites (Murphy et al., 1972; Savino et al., 1972a and b).

2. Surface waves with periods between 30 and 50 seconds were recorded from more than 90% of the 465 observed events. This percentage is greater than that for the number of events for which surface waves with periods near 20 seconds were observed. The numbers inside the heavily stippled sections of the columns that pertain to the VLP sites in Figure 3a refer to those reported events for which no body or surface waves were observed at a particular location. The seismograms during these time intervals were nominally quiet in terms of microseisms, background earth or instrumental noise, and showed no signs of seismic waves from other larger events (coda).

The numbers in the open sections of the VLP columns and the additional numbers in the hatched sections of the TLO, OGD, and KON columns designate the numbers of reported events that were masked by either body waves and/or surface waves (coda) from a larger event (open sections) or masked by large amplitude microseism storms comprised of surface waves with periods near 16 to 20 seconds. Note that the severity of the masking problem ranges from 46% of the events considered at KON to 16.4% at FBK. The effect of combining all nine VLP stations is to reduce the number of masked events to 100 out of 840 or 12%. Actually the number or percentage of masked events based on all the VLP stations (12% here) for the most part will not be significantly smaller than the smallest number or percentage obtained at some one station (e.g., FBK 137). This is a result of the well developed, and widely recorded, coda of surface waves associated with shallow events of magnitudes

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greater than 5.0 to 5.5. During the ISM month 2 events with magnitudes greater than 6.0 occurred and were responsible for 50 of the 100 events masked.

During the winter months in the northern hemisphere, and especially in the north Atlantic, microseism storms of both the double frequency (7 to 9 sec) and primary frequency type (15 to 18 sec) are particularly common. For instance microseism storms that occurred during the ISM month accounted for as much as 33% of the visual masking problem at KON. In this regard, however, it is interesting to note, although well understood (Haubrich and McCamy, 1969; Hasselmann, 1963), that while several double frequency storms were observed on the low-gain or standard seismograms from KIP, because of the structure of the Hawaiian Islands (the absence of a sloping shelf) there were no observable primary frequency storms. Thus, in terms of masking, the long-period (T>15 sec) detection thresholds determined during the ISM at this mid-ocean station depended only on the coda problem discussed above.

As both microseism storms and the occurrence of large magnitude earthquakes are transitory phenomena it is of interest to compare the performance of the nine VLP stations during a time interval when both of these masking sources are active with a time interval when both sources are absent. In Figure 3b, the performance of the VLP stations during two 48 hour time periods within the ISM month are compared. The time interval on the left-hand side corresponds to the absence of large earthquakes and microseisms while that on the right-hand side corresponds to the dominance of one or both sources. Note the drastic change in the detection capabilities from 72 out of 90 (80%) during quiet times to 19 out of 90 (21%) reported events being observed when masking is severe.

The corresponding percentage change in the number of masked events is tenfold. While masking is obviously a problem with the VLP systems, it must again be pointed out that all the results presented so far are based only on visual analysis of analog recordings. It is to be expected that some rather simple filtering techniques (low-pass, band- pass) and the more sophisticated techniques of matched filtering and polarization filtering (Choy and McCamy, 1973) that can be applied to the digitally recorded data at these sites will improve (lower) the detection thresholds, especially during recording intervals that are visually dominated by either microseisms or interfering events.

A final point to be considered concerning the results in Figure 3a is the question as to how do the VLP stations fare detection - wise when only shallow (here taken as $h < 50km$) events are considered. Figure 3c gives the answer to this question. Comparing the right-hand (all depths) and left-hand side of this figure, we find that the percentages of events observed (SIG), not observed (NO SIG), and masked do not change when the ISM listing is screened for deeper events. To some extent this result is surprising. One possible explanation, however, is that depths greater than normal ($h > 33km$) were in many instances not assigned to the very small magniutde events. This is not unexpected since the very small events were probably poorly recorded making proper depth determination extremely difficult.

C. Detection Thresholds versus Epicentral Distance:

Detection thresholds for long-period surface waves as a function of epicentral distance were previously discussed by Savino et al. (1972b) and Evernden et al. (1971) for a few of the original VLP stations. The

installation of additional VLP stations and the availability of the ISM listing prompted us to reconsider this problem.

For this study all those events listed in the ISM as having a focal depth of 50km or less, and assigned a body-wave magnitude (m_b), were considered. In Table 1 values of the 90% detection thresholds in two different 10^o distance ranges are given in terms of m_b for 5 of the VLP stations. Because of insufficient data at CTA and EIL in the 20^o to 30^o distance range threshold values were instead determined in the 30^o to 40^o range at these two stations. From Table 1 we find that mean values of the 90% detection thresholds for surface waves range from $m_b = 4.2$ at 30^o to about $m_b = 4.7$ at 90^o. It should be noted again that these threshold values are based on visual analysis of seismograms and that the filtering techniques described by Choy and McCamy (1973) should lower these values by at least 0.2 m_b units.

A paper describing the results of the detection and discrimination capabilities of the VLP stations based on the ISM listing is in preparation (Savino et al., 1973).

D. <u>General Seismological Investigations</u>;

Various investigations employing the VLP analog and digital data are currently under way. These include:

a.) A study of the sources of long-period earth noise. In particular Murphy and Savino (1973) noted the very slow decay rate with depth of especially the vertical component of earth noise at periods longer than about 25 to 30 seconds. Increasing evidence, both by us and Sorrells and Douze (1973), is beginning to point to infrasonic waves, long-period acoustic waves, as an

important source of long-period earth noise. With the cooperation of people from the National Center for Atmospheric Research in Boulder, Colorado, we are collecting infrasound information from microbarographic arrays in the United States, Bolivia, and Israel to test for the generation of earth noise by infrasonic waves at the corresponding VLP sites (ALQ, OGD in the U.S.; ZLP in Bolivia; and EIL in Israel).

b.) First motion determinations and fault plane solutions. The high-magnification data at long-periods are proving to be extremely valuable for the determination of the proximity of a particular station to a nodal plane, and thus the determination of fault plane solutions using long-period body waves.

c.) A study of dc tilts associated with large ($M_s \geq 7.5$) earthquakes, earth tidal tilts, and background secular tilts observed on the displacement outputs at the VLP stations. To date, dc tilts have been observed at CTA after a large (M_s = 8.0) New Guinea shock and at OGD after a M_s = 7.6 earthquake is Sitka, Alaska. Additional large earthquakes are being investigated and the observed dc tilts, as well as dc strains, will be compared with theoretical calculations.

TABLE 1

90% surface wave detection thresholds (m_b)

	20^o to 30^o	30^o to 40^o	80^o to 100^o
CTA		4.0	4.9
EIL		4.2	4.9
ALQ	~ 4.2		4.4
KON	4.0		4.5
TLO	~ 4.5		4.7

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*Papers published or prepared under contract F44620-71-C-0082.

FIGURE CAPTIONS

Figure 1. Schematic representation of surface-wave radiation patterns for faulting mechanisms anticipated in the northern Gulf of California. Note the optimum azimuthal position to AIQ for discriminating between the two types of faulting.

Figure 2. a) Portions of AIQ seismograms showing surface waves from two swarm events. Recordings start at 02:34, with all components normalized to the same magnification.

b) The same data with horizontal components rotated into equivalent radial and transverse components. Note strong Love-wave motion on transverse component.

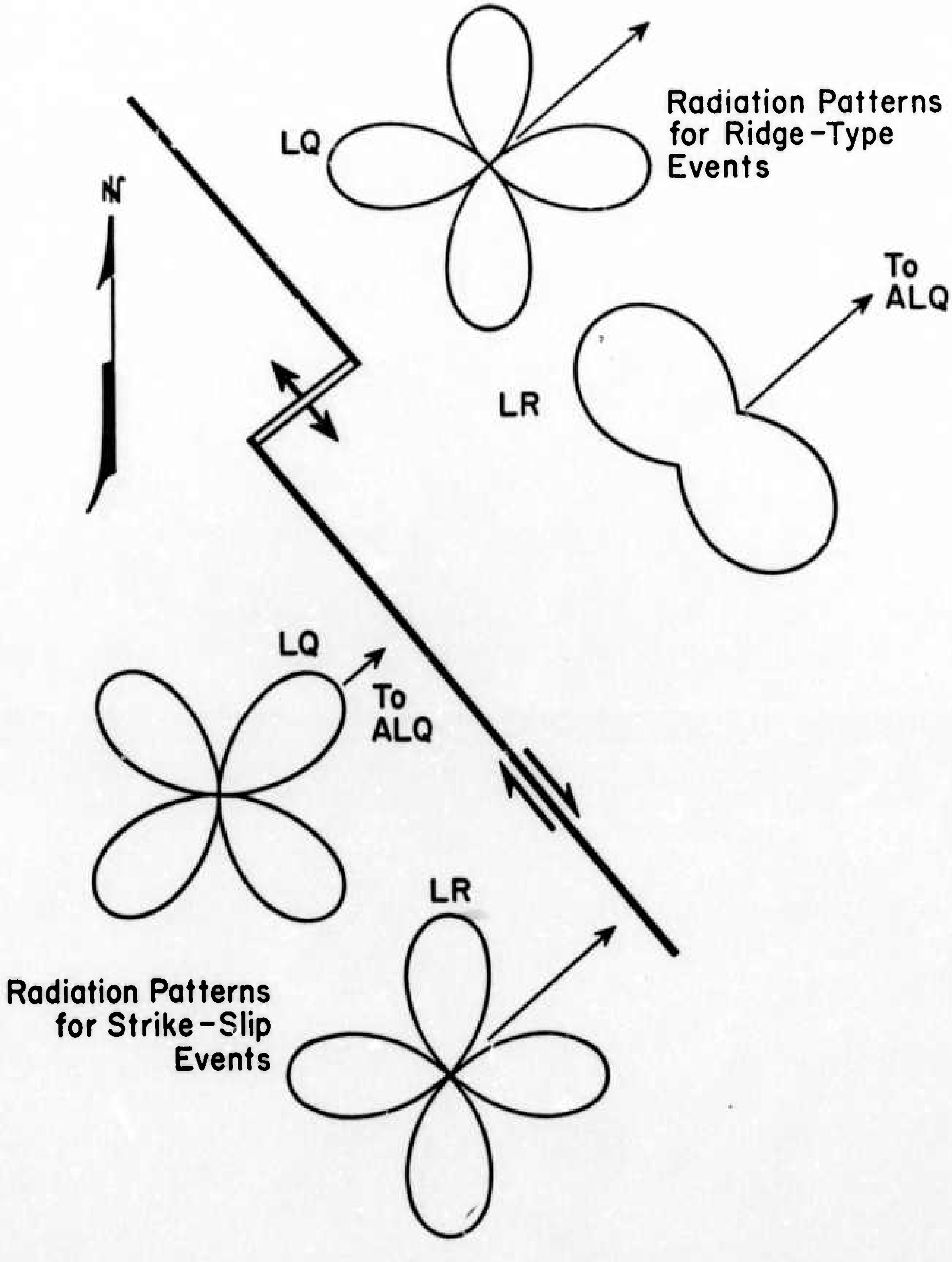
c) Same as Figure 2a - for portion of traces starting at 04:49.

d) Same as Figure 2b - for portion of traces starting at 04:49.

Figure 3. a) Histogram comparing the detection capabilities of each of the VLP stations with the ISM.

b) Histogram comparing the detection capabilities of the nine VLP stations during a quiet 48 hour time interval (left-hand side) and a 48 hour time interval during which masking is severe (right-hand side).

c) Histogram comparing the detection capabilities of the nine VLP stations for events of either shallow focal depths ($h \leq 50km$) or $h > 50km$.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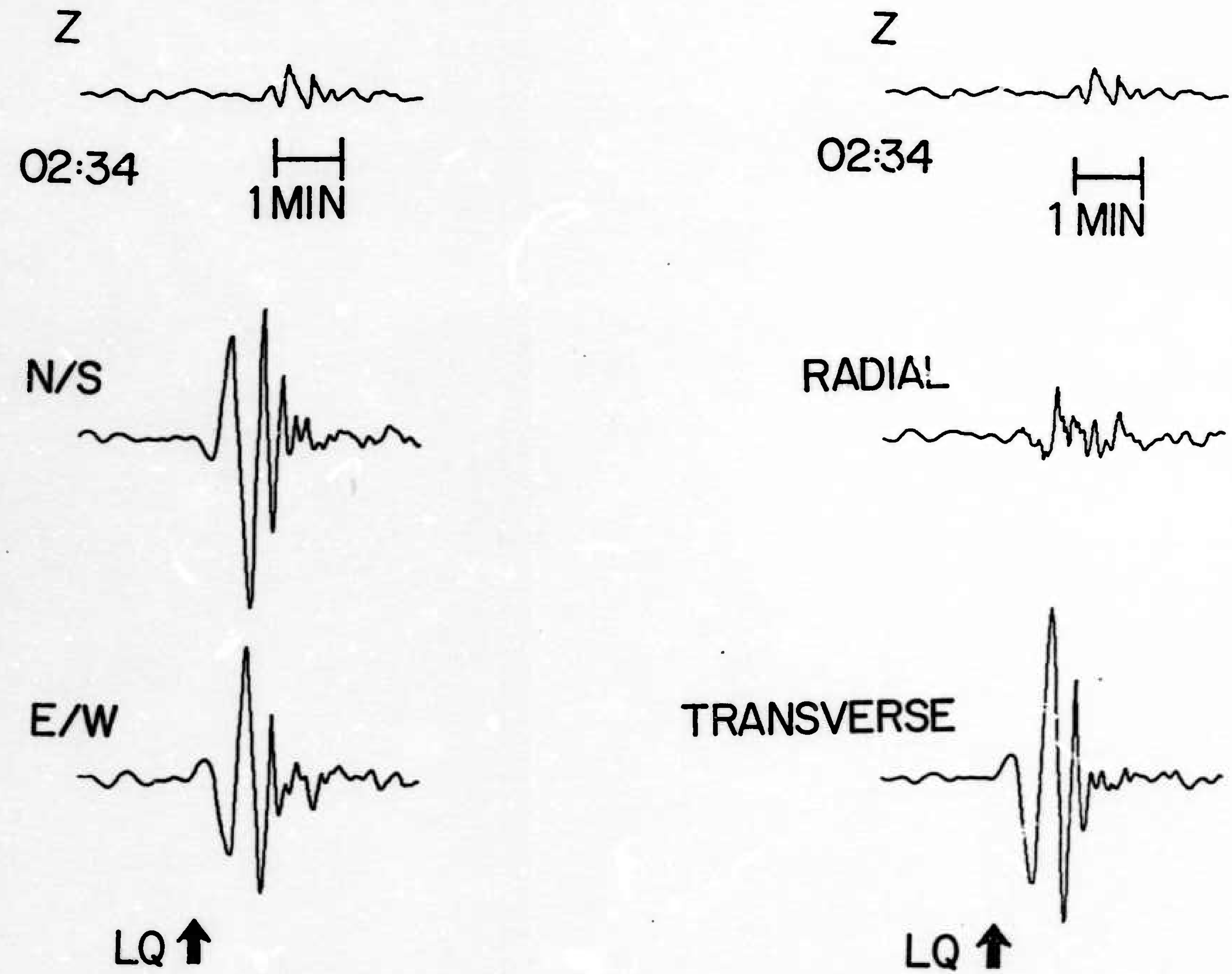
Radiation Patterns
for Strike-Slip
Events

FIGURE 1



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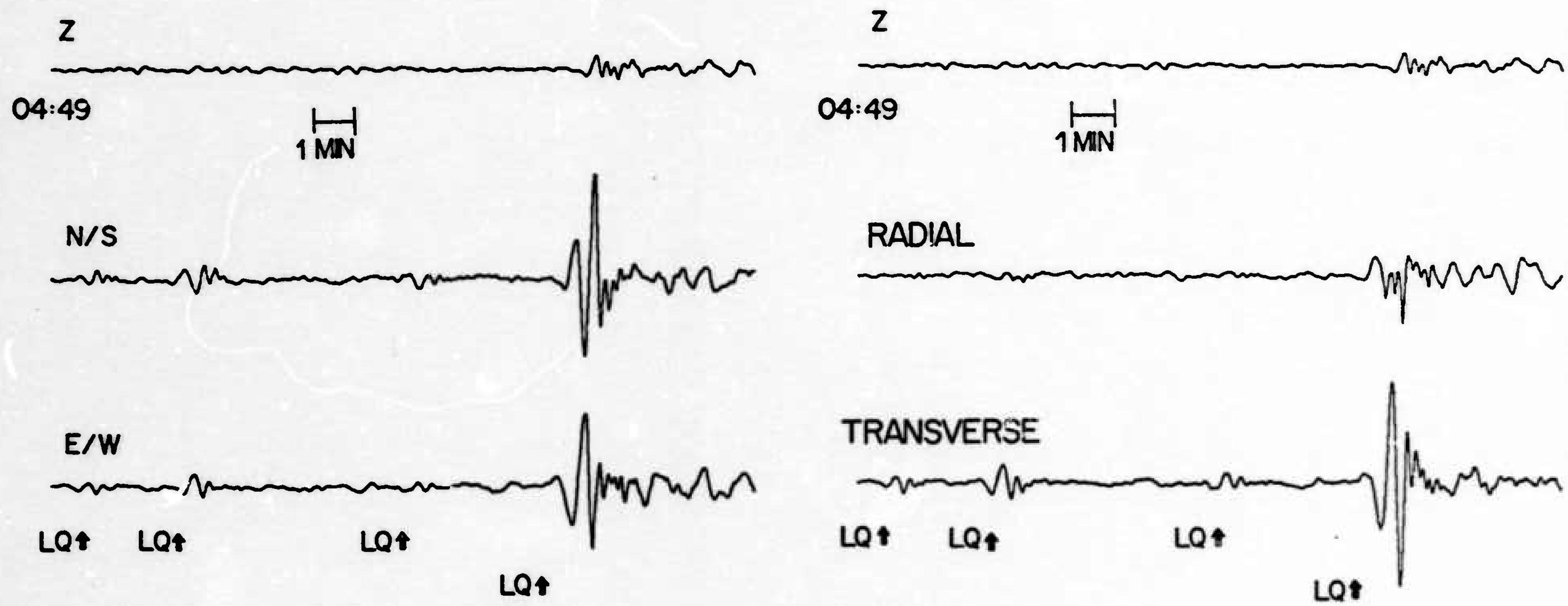
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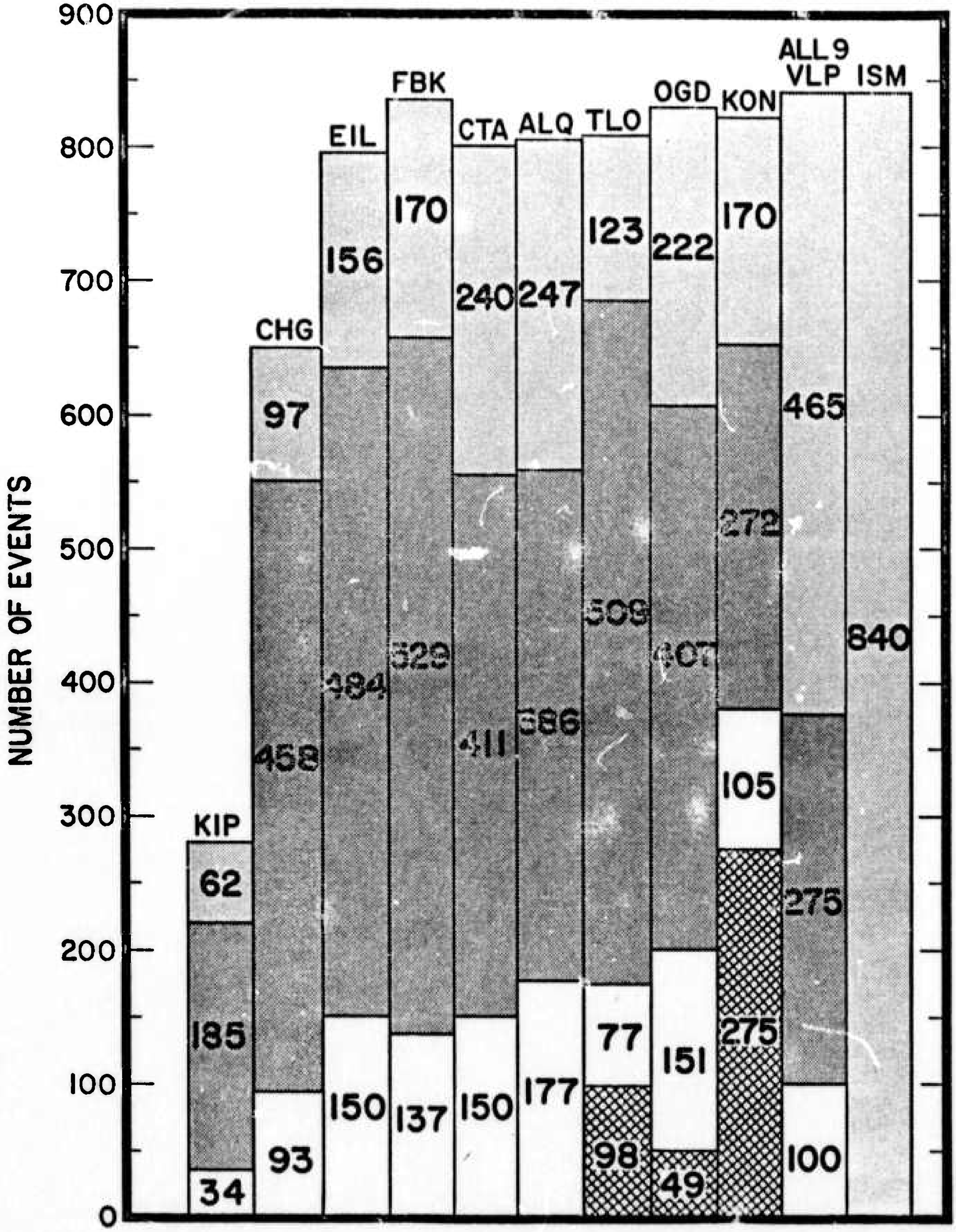

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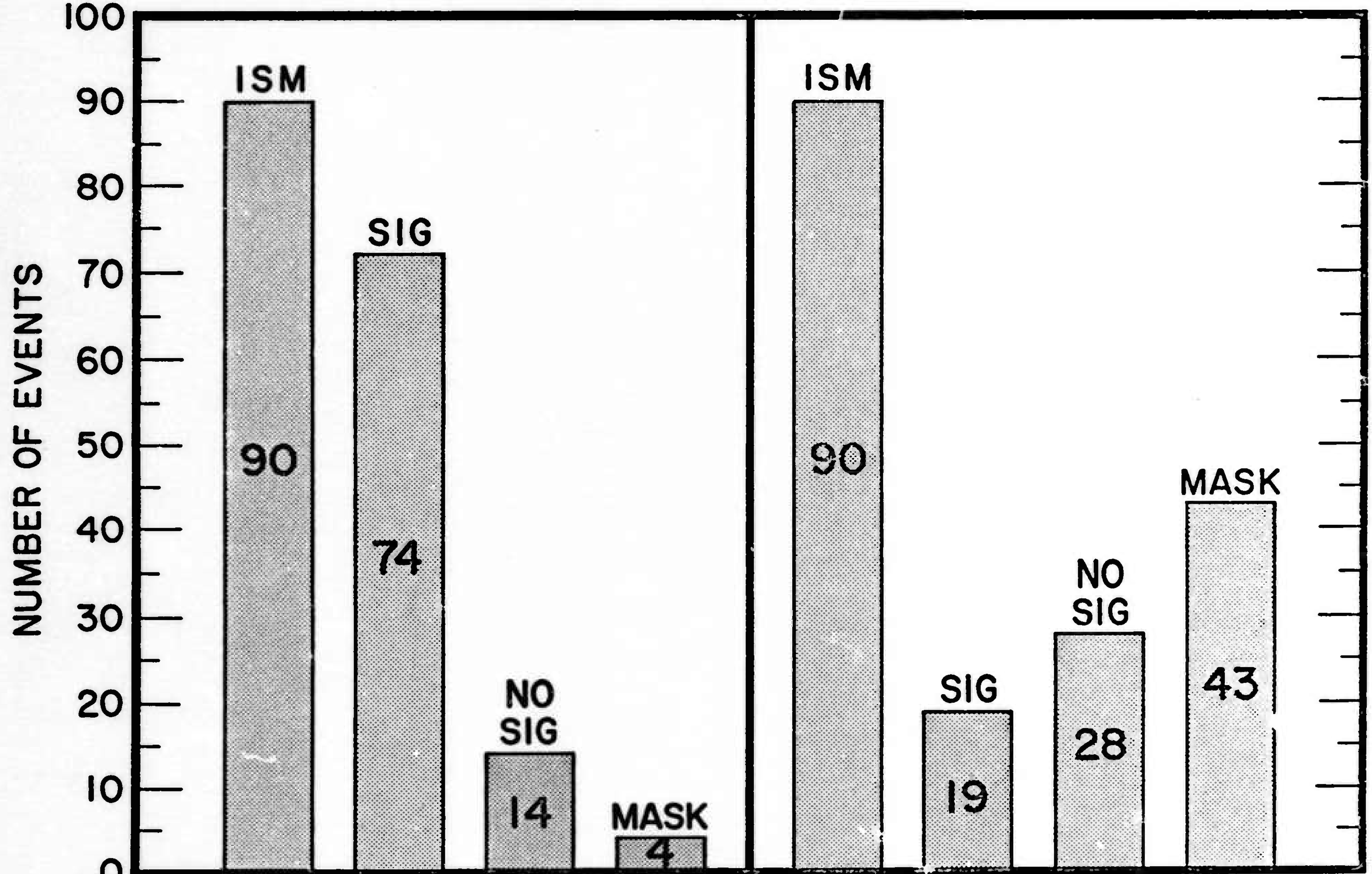
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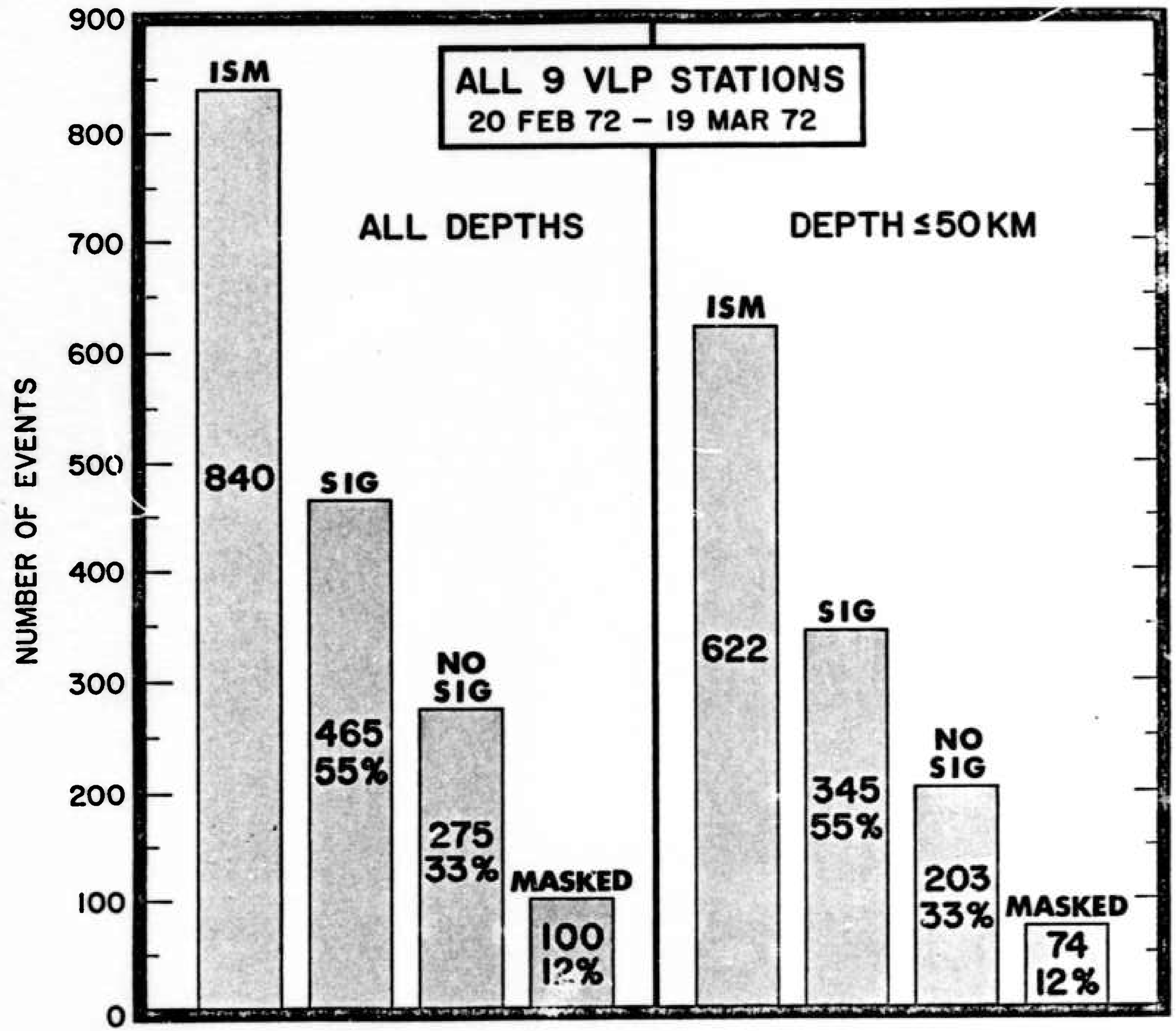
43

3b


ALL 9 VLP STATIONS
20 FEB 72 – 19 MAR 72
ALL DEPTHS
DEPTH ≤50 KM
NUMBER OF EVENTS
900
800
700
600
500
400
300
200
100
0
ISM
840
SIG
465
55%
NO SIG
275
33%
MASKED
100
12%
ISM
622
SIG
345
55%
NO SIG
203
33%
MASKED
74
12%